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SUPERDEFORMED ROTATIONAL BANDS IN ^{240}Pu*

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The intermediate structure of the fission resonances has been observed in ^{240}Pu. A resonance structure found around the excitation energy of 4.5 MeV was interpreted as a group of $K^{\pi} = 0^{+}$ superdeformed rotational bands. The moments of inertia and level density distributions were also deduced for the individually observed band-heads.

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1. Introduction

The β-vibrational states of the second minimum in the potential energy surface of the actinides calculated by Strutinsky's shell-correction method have so far been investigated as fission resonances in near-barrier excitation energies [1]. This is a direct consequence of the fact that the vibrational motion of the β-phonons represents doorway states to fission.

A moderate level density of superdeformed intrinsic states in the vicinity of the β-vibrations leads to a distribution of their fission width, which could enable the individual observation of these states. The intermediate structure of the fission resonances in ^{240}Pu was already observed by Glässel *et al.* [2], but the assignments of rotational states have not been attempted yet.

In our previous work we reinvestigated similar intermediate structures in ^{234}U and ^{236}U, where the identified spin assignments could be interpreted as

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hyperdeformed rotational bands [3,4]. On this basis we aimed at studying the fission resonances in ^{240}Pu by the high resolution measurement of the fission probability using (d,p)-reaction.

2. Experiments

The experiments were carried out at the Munich Tandem accelerator using the $^{239}\mathrm{Pu}(d,p\text{-f})^{240}$ reaction ($Q_{\mathrm{GS}} = 4.309$ MeV) at $E_d = 12.5$ MeV beam energy. The enriched (99.9%) targets of $^{239}\mathrm{Pu_2O_3}$ were $\approx 30\,\mu\mathrm{g/cm^2}$ thick and had a carbon backing of $30\,\mu\mathrm{g/cm^2}$.

The high resolution analysis of the excitation energy of the compound nuclei was performed by determining the energy of the outgoing protons with a Q3D magnetic spectrometer, which was set at 130° with respect to the beam axis. The incoming position of the protons in the focal plane was determined by a composite single (resistive) wire proportional chamber, which covered a 2 MeV wide energy region and resulted in a resolution of about 7 keV. A single-wire detector has the advantage of a rather smooth efficiency along their sensitivity axis, unlike the multi-wire detector applied in the work of Ref. [2] that could result in spurious peaks due to the strong deviations in the efficiency of the wires.

In order to deduce the fission yield *versus* the excitation energy the fission fragments also had to be detected in coincidence with the protons. For this purpose fission detectors were developed in Debrecen, which could also analyze the spatial distribution of the fragments, thus giving information on their angular distribution [5]. Each fission detector contained two position sensitive avalanche counters placed at perpendicular geometry to each other allowing two-dimensional position determination.

3. Experimental results and discussion

The measured proton spectrum in coincidence with the fission fragments is shown in Fig. 1(a). Both vibrational resonance groups at 4.5 and 5.1 MeV were observed and resolved into substates, whose strength distribution reflected the Lorentzian dependence of the picket-fence model of the strength function formalism. At the excitation energies in question, about 1 MeV below the barrier, the width of the vibrational damping has an optimum value to provide considerable fission strength to the superdeformed intrinsic states within a 200–300 keV wide region. The sparse structure of the 4.5 MeV group can be understood in terms of the lower level density and the weaker coupling through the inner barrier that keeps the physical width below the experimental resolution. In the region of the 5.1 MeV group the observed structure of highly overlapping peaks is the consequence of the higher level density and the increase in the resonance width caused by the stronger damping and the coupling of states through the inner barrier.

In the resonance group at 4.5 MeV three well-separated patterns at $E^* =$ 4434, 4526 and 4625 keV appeared possibly forming three rotational bands with the same K^π quantum number and with a moment of inertia that was found to be equal to the value of the fission isomeric band [6].

The proposed assignment of angular momenta $J^\pi = 0^+, 2^+, (4^+)$ to the observed peaks was confirmed by the analysis of the fission fragment angular distributions, which were fitted with even order Legendre polinomials up to fourth order. In order to perform a reliable comparison of the experimental angular distributions, *i.e.* their Legendre polinomial coefficients (a_0=1, a_2, a_4) to the theoretical ones calculated for different angular momenta J^π and K^π, the whole resonance structure was fitted with the suspected rotational bands (Fig. 1(a)). The different angular momentum components of the fit were weighed with the corresponding theoretical a_2, a_4 coefficients resulting in semiempirical functions, which are compared to the experimental values in Fig. 1(b) and 1(c). The considerable agreement within the experimental errors confirmed the reliability of the proposed assignments.

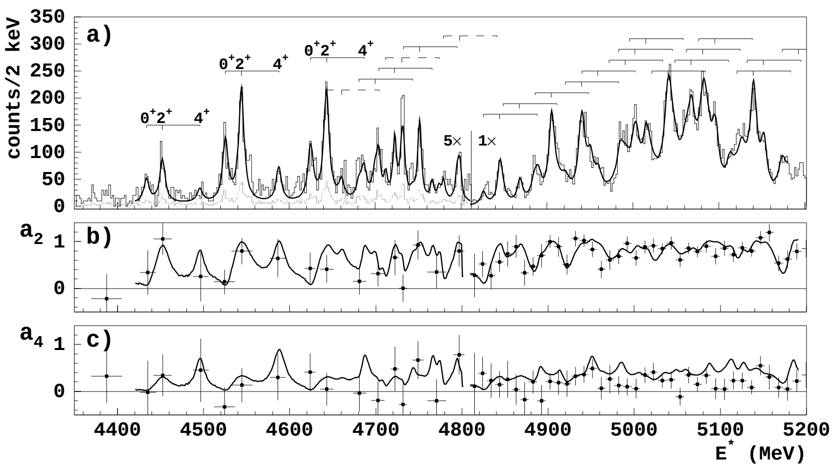

Fig. 1. (a) Proton spectrum measured in coincidence with the fission fragments; (b), (c) second and fourth order angular distribution coefficients of the fission fragments in comparison with the calculated values for $K^\pi = 0^+$ bands (see the text).

The resonance group at 5.1 MeV that showed a more damped and overlapping structure, could also be nicely reproduced, which, however, does not provide a satisfactory and reliable description on its intermediate structure, oppositely to the case of the 4.5 MeV group.

By the argument of confident selection of $K^\pi = 0^+$ states complete spectroscopy can be performed in the regions of the vibrational damping.

In order to check this completeness and the consistency of the observed level density with the excitation energies with respect to the superdeformed ground state, a statistical analysis of the level distances was performed using the band-head energies of the fit. The consistency was satisfactory when applying a ground state energy of 2.25(20) MeV, which was in good agreement with the results of excitation function measurements [7].

The moment of inertia, which sensitively reflects both the nuclear deformation and collective structures of the excitations, could for the first time be extracted at such high excitation energies of the 4.5 MeV resonance group for the three well separated bands at $E^* = 4434$, 4526 and 4625 keV. An average value of $\Theta = 157 \pm 9$ MeV^{-1} was deduced that was found to be very similar to that of the superdeformed ground state rotational band [6].

Another important aspect of the collectivity is the series of the β-vibrations in the second minimum. In the conversion electron measurements of Ref. [8] the phonon energy of the first β-vibration was determined as $\hbar\omega = 769.9$ keV. With respect to the excitation energy of the superdeformed ground state ($E_{\mathrm{II}} = 2.25(20)$ MeV) determined by the statistical analysis of the level distances above, the vibrational resonances centered around 4.5 and 5.1 MeV could be attributed to three and four β-phonon excitations, respectively. The somewhat reduced energy difference of 600 keV between the vibrational states is not surprising, because the potential well opens up at the top of the barrier. The observation of subsequent β-vibrations in transmission resonances can provide a unique possibility to study slightly anharmonic vibrational series at large nuclear deformations in a more convenient way than in the ground state minimum, where the high level density results in a complete damping of the fission widths.

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